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STEPS TOWARD THE HUBBLE CONSTANT. VIII. THE GLOBAL VALUE

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ABSTRACT

A new calibration is given of the mean absolute magnitude of the three brightest red and blue supergiant stars in nearby galaxies whose distances are independently known from Cepheid variables. The calibration covers 7 magnitudes in M_B of the parent galaxy and shows $\langle M_V(3)\rangle$ for *red* supergiants to be constant at -7.72 ± 0.06 with dispersion of $\sigma=0.17$ mag. However, $\langle M_B(3)\rangle$ for the brightest *blue* supergiants varies nearly in step with M_B(galaxy) for parent galaxies brighter than $M_B=-17$, making such blue stars less useful as distance indicators.

The brightest red supergiants have been identified and measured in the three nearby, resolved galaxies IC 4182, NGC 4214, and NGC 4395 to obtain distance moduli of $(m-M)^0=28.21$, 29.02, and 28.82, respectively. These distances are used to calibrate the mean absolute magnitude at maximum of the two Type I supernovae (SNe I) 1937c and 1954a, after showing that $\sigma(M)$ for SNe I is small, and hence that such stars are also good distance indicators.

The value $\langle M_B(\max)\rangle_{\text{SNe I}}=-19.74\pm0.19$ is used to calibrate the velocity–apparent magnitude (Hubble) diagram for 16 SNe I, most of which have recession velocities greater than 3000 km s^{-1}, beyond the effect of any local velocity anisotropy. The result is that the global value of the Hubble constant is $H_0=50\pm7$ km s^{-1} Mpc^{-1}. Agreement with $H_0=46\pm6$ km s^{-1} Mpc^{-1}, required by time-scale arguments for a Friedmann cosmology with $q_0=0$, is noted.

Subject headings: cosmology — galaxies: redshifts — galaxies: stellar content — stars: luminosities — stars: supergiants

I. INTRODUCTION

The local value of the Hubble constant, even if it could be determined with precision, is expected to differ from the global value due to the large density enhancement of the Virgo complex. This North Galactic Anomaly should cause a systematic perturbation of the global Hubble flow at some level, unless $q_0=0$ (or conversely if q_0 were *very* large due to a presently unseen uniformly distributed substratum mass, causing the density contrast of the Virgo complex to be, in fact, insignificant).

The question of the existence and especially the size of any real velocity perturbation remains controversial —so much so that no convincing value of H_0(global) can be expected from methods that rely on measured velocities smaller than ~3000 km s^{-1}. Hence, precision distances are required to galaxies well beyond the Virgo complex.

In earlier papers of this series (cf. Sandage and Tammann 1976, Paper VII with earlier references; hereafter ST VII) we attempted to cross the local region into the unperturbed Hubble flow using H II region diameters and then Sc I galaxies alone as distance indicators, after establishing the local distance scale to the M81/NGC 2403 and the M101 groups (Tammann and Sandage 1968; ST II, III), first from Cepheid variables, and then from brightest stars using Cepheids.

Unfortunately, the last stage of this bridge into the zone where $v>3000$ km s^{-1} is less certain than we first believed due to a new understanding that the van den Bergh luminosity classes, even for Sc I galaxies, do not measure luminosity, except within wide limits (Tammann, Yahil, and Sandage 1979).[3]

In the present paper we again approach the problem of finding H_0(global), but now by using two distance indicators whose dispersion in absolute magnitude is

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[3]Although we now believe that the last step in ST VI did give nearly the correct value for H_0(global), it did so by the lucky circumstances that (1) the Malmquist bias of our *two* samples of Sc I galaxies (one bright and the other faint) caused the mean absolute magnitude $\langle M\rangle$ of each sample to be nearly the same (despite the large range in *apparent* magnitude between them) because each sample was chosen from two different catalogs (one the Shapley-Ames and the other the Zwicky volumes) whose apparent magnitude limits were different, and (2) our adopted $\langle M\rangle_{\text{Sc I}}$ was fortuitously correct for the *mean* of these two samples with different Malmquist biases.

small, and hence which are virtually free from the Malmquist bias. In § II we present new data on the mean absolute magnitude of the brightest individual red and blue supergiant stars in very nearby galaxies, calibrated relative to the Cepheids. As a next step, the red supergiants have been found and measured in IC 4182, NGC 4214, and NGC 4395 using yellow and blue plates taken in good seeing. The results, set out in § III, are used to calibrate $\langle M_B^{\max} \rangle$ for two well-observed Type I supernovae (SNe I), one in each of the first two galaxies. Proof that SNe I are good standard candles with small dispersion in $\langle M \rangle$ is summarized in § IV. The velocity-relative distance diagram for 16 SNe I with known $m_B^{\max}$ is then calibrated in § IV*b* using the distances for IC 4182 and NGC 4214, with the result that $H_0(\text{global}) = 50 \pm 7$ km s^{-1} Mpc^{-1}. No ad hoc assumptions or tertiary calibrations are necessary. The result is compared in § V with the known age of globular clusters in the Galaxy (increased by the Galaxy formation time) to show that the cosmological and the evolutionary time scales now closely agree if $q_0 \approx 0$.

II. ABSOLUTE MAGNITUDES OF BRIGHTEST RESOLVED STARS

a) *Via Cepheids*

Three additional galaxies can be added to the original calibration (ST II) of the brightest resolved red and blue supergiants in galaxies whose distances are known, either from Cepheids directly or from groups where at least one galaxy has a Cepheid distance. (1) New work in M33 (Humphreys and Sandage 1980) permits identification and photometry of its brightest red and blue stars. (2) Color-magnitude diagrams to $V = 22$, $B = 23$ have been obtained for Sextans A (Sandage and Carlson 1982) and Holmberg IX (Sandage 1982*a*), which is the immediate eastern companion to M81.

The data for these and the other calibrators, known earlier, are set out in Table 1. Column (2) lists the adopted blue modulus from the indicated sources,[4] column (3) the adopted blue absorption, column (4) the fully corrected blue absolute magnitude, including the correction for internal absorption (Kraan-Kortweg and Tammann 1979), columns (5) and (7) list the mean blue and yellow apparent magnitudes of the three brightest stars from the sources given at the bottom of the table, and finally, columns (6) and (8) give the corresponding absolute magnitudes. The calibration of the red supergiants at $\langle M_V(3) \rangle = -7.72 \pm 0.06$ has the small standard deviation of $\sigma = 0.17$ mag.

b) *Via Red Stars in Seven Other Galaxies*

The data in Table 2 are also from new color-magnitude diagrams (Sandage 1982*a*), photoelectrically calibrated. The observed mean magnitude of the three brightest red stars in column (2) are used, via the red star calibration obtained in the last section, to find $(m - M)^0$ in column (4) using the adopted absorptions in column (3). From these data, the $M_B^0(3)$ absolute magnitudes follow in column (6), and the absolute magnitudes of the parent galaxies in column (7). The listed moduli and absolute magnitudes are believed to be accurate to $\sim \pm 0.3$ mag individually.

c) *The New Calibration*

The data, plotted in Figures 1*a* and 1*b* for the red and blue stars, respectively, show no correlation of M_V(red star) with M(galaxy), but show a pronounced correlation for the blue stars, as in the original calibration (ST II). The correlation begins in galaxies brighter than $M_B(\text{galaxy}) \approx -17$, hence blue stars in such galaxies are less useful as distance indicators because the correlation line is almost 45°, which is the degenerate condition for which faint, nearby indicators imitate bright distant ones exactly.

The most important features of Figure 1*a* for our problem are (1) the tightness of the spread of M_V for the red supergiants, and (2) the constancy of M_V(star) over 7 magnitudes of M(galaxy).[5]

[4] These distance moduli are conservative, based still on the old modulus of the Hyades of 3.03 (van Bueren 1952; Wayman, Symms, and Blackwell 1965; Eggen 1979). If a larger distance modulus (e.g., van Altena 1974; Hanson 1975) were adopted, our absolute magnitudes for the resolved stars would become brighter because the modulus to the parent galaxy becomes correspondingly larger due to the direct effect on the adopted *P-L-C* relation (Sandage and Tammann 1969, 1971) for Cepheids. Graham's (1973, 1975, 1977) RR Lyrae stars in the Magellanic Clouds do not support the increase (cf. Tammann, Sandage, and Yahil 1980). The smaller moduli adopted here are independently confirmed to within $\sim \pm 0.2$ mag in the LMC by Cepheids (Martin, Warren, and Feast 1979), by Mira stars (Glass and Evans 1981), and by OB stars (Crampton 1979), and for the SMC by Cepheids (Feast 1977) and by OB stars (Crampton and Greasley 1981), which partially, however, also depend on the Hyades modulus.

[5] Our value of $M_V(3) = -7.72 \pm 0.17\sigma$ is ~ 0.3 mag fainter than $M_V(3) = -8.0$ adopted by Humphreys (1980*c*, Paper VI with earlier references therein) primarily because of our different approach to the problem of internal absorption. We have chosen not to apply such corrections because, in general, they are almost always unknown for the program galaxies, in contrast to some of the nearby calibrators where many of the red stars have been individually photometered by Humphreys. We justify our procedure by noting that (1) the brightest stars in a galaxy as seen by an outside observer are expected to be biased in favor of low internal absorption, and (2) the internal absorption may increase the magnitude scatter but will not introduce a *systematic* error in distance as long as the calibrating and the unknown galaxies are treated consistently. But, of course, our $M_V(3)$ value is fainter than that of Humphreys because she does apply corrections to her calibration data. Hence, to use her value, one must make some assumption concerning the internal absorption for the unknown (program) galaxies, whereas no assumption is needed in the method used here.

TABLE 1

THE BRIGHTEST BLUE AND RED STARS FROM CEPHEID DISTANCES

Galaxy (1)	$(m-M)_{AB}$ (2)	A_B (3)	$M_B^{0,i}$ (gal) (4)	$m_B(3)$ (5)	$M_B(3)$ (6)	$m_V(3)$ (7)	$M_V^0(3)$ (8)
Solar neighborhood ...	...	...	(−18.5)[1]	...	−8.84[2]	...	−7.97[3]
LMC	18.91[4]	0.32[4]	−18.44	9.46[5]	−9.45	11.07[6]	−7.76
SMC	19.35[4]	0.08[4]	−16.81	10.63[5]	−8.72	11.77[7]	−7.56
M33	24.68[4]	0.12[4]	−18.87	15.72[8]	−8.96	16.70[8]	−7.95
NGC 6822	25.03[4]	1.08[4]	−15.84	16.89[9]	−8.14	16.94[9]	−7.82
IC 1613	24.55[4]	0.12[4]	−14.71	16.68[10]	−7.87	16.95[10]	−7.57
Sextans A	25.67[11]	0.07[11]	−13.97	17.88[11]	−7.79	18.09[11]	−7.53
NGC 2403	27.80[4]	0.24[4]	−19.37	18.27[12]	−9.53	20.07[13]	−7.67
NGC 2366	27.76[4]	0.19[4]	−16.53	18.97[13]	−8.78	...	...
NGC 4236	27.58[4]	0.02[4]	−18.21	19.22[13]	−8.36	...	...
IC 2574	27.60[4]	0.04[4]	−16.87	19.77[13]	−7.83	(20.0)[13]	(−7.6)
Ho II	27.67[4]	0.11[4]	−16.58	19.64[13]	−8.03	(20.4)[13]	(−7.2)
Ho I	27.63[4]	0.07[4]	−14.40	19.73[13]	−7.90	...	...
Ho IX	27.63[14]	0.07[14]	−13.45	19.56[14]	−8.07	(19.5)[14]	(−8.1)
M101	29.2[15]	0.00[15]	−21.31	18.99[16]	−10.21	$\gtrsim$21.2[17]	$\gtrsim -8.0$
NGC 5474	29.2[15]	0.00[15]	−18.19	20.6[17]	−8.6	...	...
NGC 5585	29.2[15]	0.00[15]	−18.26	20.9[17]	−8.3	...	...
							−7.72±0.06 $\sigma=0.17$

SOURCES.—[1]Assuming for our Galaxy $M_B \approx -21.0$ mag and that the solar neighborhood is representative for 1/10 of the Galaxy. [2]Mean for ρ Cas, ζ Sco, and HD 134959 (Humphreys 1978). [3]Mean for μ Cep, KY Cyg, and KW Sgr (Humphreys 1978). [4]Sandage and Tammann 1974*a* (ST I). [5]Feast, Thackeray, and Wesselink 1960. [6]Humphreys 1979*a*. [7]Humphreys 1979*b*. [8]Humphreys and Sandage 1980. [9]Kayser 1967; Humphreys 1980*a*. [10]Sandage and Katem 1976; Humphreys 1980*a*. [11]Sandage and Carlson 1982. [12]Sandage and Tammann 1974*b* (ST II); Humphreys 1980*b*. [13]Sandage and Tammann 1974*b* (ST II). [14]Sandage 1982*a*. [15]Sandage and Tammann 1974*c* (ST III), 1981. The distance limit is required by the absence of Cepheids in M101. [16]Sandage and Tammann 1974*c* (ST III); Humphreys 1980*b*. [17]Sandage and Tammann 1974*c* (ST III).

TABLE 2

NEW DISTANCES FROM RED SUPERGIANTS

Galaxy (1)	$m_V(3)$ (2)	A_V (3)	$(m-M)^0$ (4)	$m_B(3)$ (5)	$M_B^0(3)$ (6)	$M_B^{0,i}$(gal) (7)
W-L-M	17.82	0.00	25.54	17.94	−7.60	−14.81
Sextans B	18.94	0.05	26.64	19.50	−7.17	−15.00
Leo A	19.68	0.00	27.40	18.75	−8.65	−14.49
Pegasus	20.52	0.05	28.19	20.10	−8.15	−15.84
IC 4182	20.49	0.00	28.21	20.24	−7.97	−16.87
NGC 4395 ...	21.1	0.00	28.82	19.29	−9.53	−18.47
NGC 4214 ...	21.3[a]	0.00	29.02	19.23	−9.79	−18.99

[a]The brightest red supergiant has $m_V(1) = 21.1$ mag. The mean difference $m_V(3) - m_V(1) = 0.19$ mag ($\sigma = 0.14$ mag) has been applied.

III. DISTANCES TO IC 4182, NGC 4214, AND NGC 4395 FROM THEIR RED SUPERGIANTS

Inspection of large-scale, good-seeing plates taken between 1930 and 1950 with the Mount Wilson Hooker 2.5 m reflector of these and other galaxies in the Coma–Canes Venatici–Ursa Major region had already shown the cited galaxies to be very highly resolved into individual stars. Plates of these and similar candidates have been taken as a regular program during fine seeing conditions since 1950 with the Hale 5 m reflector so as to measure their brightest stars. For these particular galaxies, photoelectric calibration has been obtained with the Hooker reflector of nearby field stars to $V = 17.5$, and the sequences were extended 5 magnitudes fainter in B and V with a Pickering-Racine wedge used with the 5 m photographic plates. The resulting color-magnitude diagrams for these galaxies (Sandage 1982*a*) give values for the brightest red and blue supergiants listed in Table 2.

IC 4182 and NGC 4395 were particularly easy objects as regards photometry of their brightest stars. The

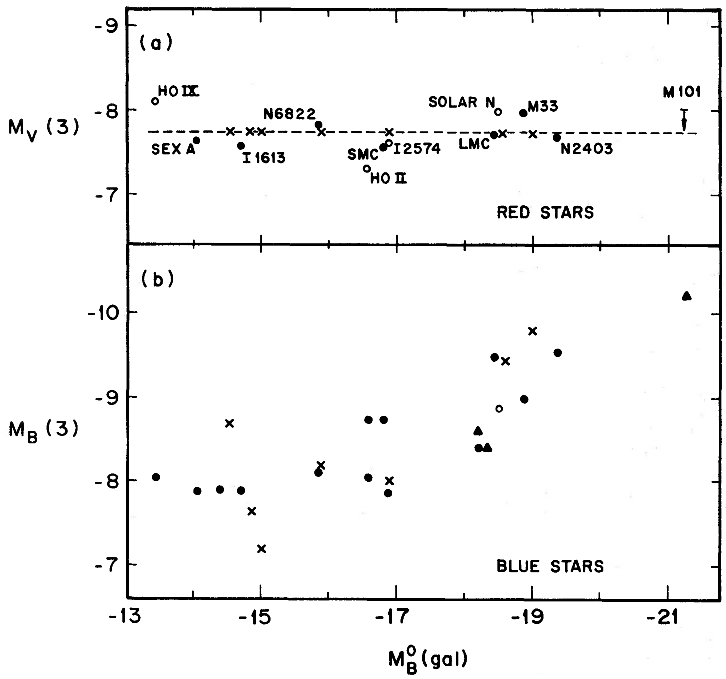

FIG. 1.—*Top*, calibration of the mean absolute V magnitude of the three brightest red supergiants in galaxies whose distances are known from Cepheids (or by other methods for the solar neighborhood). Open circles are less certain values, given in parentheses in Table 1. Crosses are galaxies from Table 2, forced to be on the mean line defined by the calibration. *Bottom*, mean absolute B magnitude for the first three brightest blue supergiants in the galaxies listed in Tables 1 and 2. Crosses are from Table 2. The three triangles are galaxies in the M101 group. The absolute blue magnitude of the parent galaxy, corrected for absorption, is plotted as abscissa.

surface brightnesses of their background galactic disks are low. Also, the galaxies have spiral features and associations, which makes the identification of the member stars by position quite straightforward.

NGC 4214 presented certain complications with field stars, and with photometry on a high background. These caused difficulties even for Argelander step-scale photometry used throughout, and the data for NGC 4214 are less certain. However, what is certain is that NGC 4214 and NGC 4395 are in a common group (Kraan-Korteweg and Tammann 1979, their group B4), hence the distance to NGC 4395 provides a good confirmation for NGC 4214.

The true distance moduli listed in column (4) of Table 2 of $(m-M)^0=28.21$, 28.82, and 29.02 for IC 4182, NGC 4395, and NGC 4214, respectively, are well determined for the first two galaxies at the ± 0.3 mag level, giving distances which we believe to be absolute, and accurate to $\sim\pm 15\%$.

IV. CALIBRATION OF TYPE I SUPERNOVAE AS DISTANCE INDICATORS

a) *Proof of Usefulness*

Problems of determining the magnitudes of supernovae at maximum and the internal absorption in galaxies of all types have been reviewed recently (Tammann 1981). Available data had suggested earlier (Kowal 1968) that the dispersion in $\langle M_B^{\max}\rangle$ may be small in well-observed SNe I, and hence that they might be good relative distance indicators. Once calibrated, they would then become good absolute indicators.

It has now become clear that a distinction should be made between SNe I in E and in spiral galaxies because of the difficult problem of internal absorption (Tammann 1981, Fig. 6). Hence, because of the lack of internal absorption, SNe I in E galaxies are particularly important. Analysis of 16 SNe I in such galaxies either of known redshift or internal to the Virgo and Coma clusters shows that $\sigma(M_B^{\max})=0.58$ mag for the complete sample, and $\sigma(M)=0.43$ mag for a subsample of the nine best observed SNe I (Tammann 1981, § 3.1).

The magnitudes at maximum of the 16 SNe I were taken from a recent analysis (Cadonau and Tammann 1982) of previous data (Barbon, Capaccioli, and Ciatti 1975; Pskovskii 1977; Kowal 1978; Branch and Bettis 1978); a conversion of the $m_{\rm pg}$ magnitudes to the B system of $m_B-m_{\rm pg}=0.24$ mag at maximum has been adopted. The magnitudes have been corrected for galactic absorption using the precepts of the *RSA* (Sandage and Tammann 1981). An absorption-free polar cap for $b>50°$, adopted there, now seems well established from new high-latitude X-ray, far-ultraviolet, and radio data (cf. Heiles 1980; Bohlin, Savage, and Drake

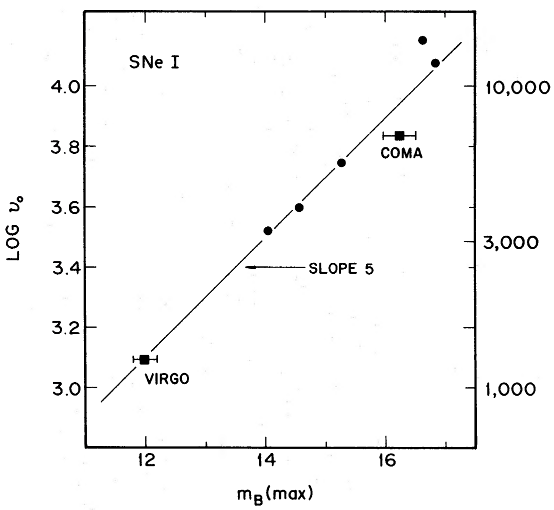

FIG. 2.—Redshift–apparent magnitude diagram for 16 Type I supernovae in E galaxies with known m_B^{max}. Six supernovae make up the Virgo cluster point, and five are in Coma.

1978). The m_B^{max} values are plotted in the Hubble diagram of Figure 2, where the six SNe I in Virgo cluster E galaxies and the five in the Coma cluster are combined.

The SNe I follow a line of slope 5 with high accuracy. Since it is independently known from first-ranked cluster E galaxies that the far expansion field *is* linear (Sandage 1972*a*, *b*), Figure 2 shows that $\langle M_B^{max} \rangle$ for SNe I is stable to within the scatter quoted above. A least-squares fit, using m_B^{max} as independent variable, and forcing a slope of 5, requires

$$\langle M_B^{max} \rangle = (-19.74 \pm 0.24) + 5 \log (H_0/50). \quad (1)$$

Another check on the stability of $\langle M_B^{max} \rangle$, which is independent of all velocity data, comes from the fact that the six SNe I in Virgo cluster E galaxies have $\langle m_B^{max} \rangle = 12.02 \pm 0.18$, again with a small scatter of $\sigma = 0.43$.[6]

Finally, an impressive demonstration that SNe I are almost perfect standard candles, has recently become available from extended infrared photometry of three SNe I, two of which lie in the *same* galaxy, NGC 1316, and one in the Virgo cluster spiral, NGC 4536 (Elias *et al.* 1981). The complex light curves of these stars are identical to within 0.1 mag, which is of the same order as the observational accuracy.[7]

b) *Absolute Calibration Using NGC 4214 and IC 4182*

Two of the galaxies in Table 2 with known distances have produced SNe I with well-observed light curves, i.e., IC 4182 (SN 1937c) and NGC 4214 (SN 1954a). Although SN 1954a has shown some spectral peculiarities, it is, with no doubt, of Type I (Oke and Searle 1974).

The relevant data for the two SNe are compiled in Table 3. Baade's (1938, 1941) maximum of $m_{pg}^{max} = 8.2$ for SN 1937c translates to $m_B^{max} = 8.44$ (col. [3]). The available color information does not allow a correction for internal absorption, and because the SN lies outside the main body of IC 4182, we have conservatively adopted zero absorption. (Note, that any absorption correction would lead to a *lower* value of H_0.) Wild's (1960) photometry of SN 1954a, together with the standard light curve of Barbon, Ciatti, and Rosino (1973*a*), gives $m_B^{max} = 10.18$.

To estimate the absorption, we have taken the shape of the $(B - V)$ light curve from the well-observed SN 1972e in NGC 5253 (Ardeberg and de Groot 1973; Lee, Wamsteker, and Wisniewski 1972) and the zero point of the color curve from the presumably absorption-free SN 1970j, which occurred in the elliptical galaxy NGC 7619 at $b = 48°$ (Barbon, Ciatti, and Rosino 1973*b*). This detour is necessary because the *published* intrinsic color curves are not independent of SN 1954a. The resulting reddening for SN 1954a is $E_{B-V} = 0.22 \pm 0.08$, which then leads (assuming $A_B / E_{B-V} \approx 4$ for SNe) to a blue absorption of $A_B \approx 0.88 \pm 0.32$, and to the corrected value of m_B^0(max) in Table 3, column (3). In column (4), the distance moduli of the parent galaxies are repeated from Table 2; however, for SN 1954a, we adopt, for reasons discussed above, the mean modulus of NGC 4214 and

[6]In passing, it may be noted that the mean apparent magnitude of the Virgo SNe I, combined with the absolute magnitude calibration from § IV*b*, gives $(m - M)^0 = 31.68 \pm 0.30$ (21.7±3.1 Mpc) for the Virgo cluster. With $H_0 = 50 \pm 7$ from below, the expected Virgo recession velocity is $v_0 = 1085 \pm 217$ km s^{-1}, while the observed value is $\langle v_{obs} \rangle = 967 \pm 50$ km s^{-1} (Kraan-Korteweg 1981). This limits our infall velocity toward Virgo to 118 ± 223 km s^{-1}. For the derivation of equation (1), a true Virgo cluster velocity, corrected for our infall motion, of 1200 km s^{-1} was adopted. An error of ±200 km s^{-1} of this velocity affects the mean absolute magnitude of the 16 SNe I by only ±0.2 mag; this error has been allowed for in the quoted error of equation (1).

[7]For the reasons stated in the two paragraphs above, we do not believe the correlation between M_B^{max} and the decline rate of SNe I, as suggested by Pskovskii (1977) and Branch (1981), to be real. The decline rate is sensitive to photometric errors due to background problems and scale errors of the photographic standards. However, if there were such a correlation, the two SNe I 1937c and 1954a are suggested to be of the "fast" and therefore "underluminous" type, and in that case the value of H_0, derived in IV*b*, would be an *overestimate*. It is, perhaps, also necessary to state that we have assumed that SNe of Type I in E galaxies have the same M_B(max) as those in spirals. This supposition is based here on the similarity of the light curves (Elias *et al.* 1981), meaning to us a highly constrained set of physics, which, following Gertrude Stein, suggests that a Type I supernova is a Type I supernova is a Type I supernova.

TABLE 3

LUMINOSITY CALIBRATION OF SNE I USING NGC 4214 AND IC 4182

Name (1)	Galaxy (2)	m_B^0(max) (3)	$(m-M)^0$ (4)	M_B^0(max) (5)
SN 1937c ...	IC 4182	8.44 ± 0.1	28.21 ± 0.2	-19.77 ± 0.22
SN 1954a ...	NGC 4214	9.30 ± 0.3	28.92 ± 0.3	-19.62 ± 0.42
				-19.74 ± 0.19

NGC 4395. Our final calibration of $\langle M_B^0(\max)\rangle = -19.74 \pm 0.19$ is in column (5).[8]

The calibration is in satisfactory agreement with presently available expansion parallaxes of SNe I and SNe II. The quoted values for SNe I are within the limits $-20.5 \leq M_B^{\max} \leq -19.12$ (Branch 1977; Arnett 1982; Branch 1981). For the type II SN 1979c in the Virgo cluster, Branch *et al.* (1981) found a distance modulus of $(m-M)^0 = 31.8$, which then requires, for the six Virgo SNe I in § IV*a*, $\langle M_B^{\max}\rangle = -19.8$.

The calibration from Table 3, combined with the Hubble diagram of Figure 2 via equation (1), requires

$$H_0 = 50 \pm 7 \text{ km s}^{-1} \text{ Mpc}^{-1}. \quad (2)$$

Because Figure 2 is mainly defined by SNe I with $3000 < v_0 \lesssim 12{,}000$ km s^{-1}, this is clearly the global value because we are well beyond the effect of any local velocity anisotropies.

V. COMPARISON OF THE TIME SCALES

One of four central tests of the Friedmann cosmology is comparison of time scales. Now that one has hope that the age of the system of globular clusters is known in the Galaxy, this test can be made using equation (2) for comparison.

To the age of the globular clusters of $(17 \pm 2) \times 10^9$ years (Sandage 1982*b*) we must add the formation time of galaxies from the "beginning." Here we have used the observed upper limit to the redshift of quasars of $z \approx 4$ (Sandage 1972*b*; Osmer 1982), to estimate this additional formation time.

[8] With this value, the two Galactic SNe (presumably of Type I) of Tycho (SN 1572) and Kepler (SN 1604) are at distances of 4.0 and 3.2 kpc from us, respectively. These distances are within the range of the published values. SN 1885a in M31 (i.e., S And) must either have been dimmed by 0.6 mag of internal absorption, or it was not of type I.

In the $q_0 = 0$ limit it is easy to show that the age of the universe, t_0, from globular clusters plus formation time is

$$t_0 = (17 \pm 2) \times 10^9 + 0.2\, H_0^{-1}, \quad (3)$$

the last term being the quasar formation time. [In the $q_0 = 1/2$ special case, where the space dilation goes as $R(t) \sim t^{2/3}$, the last term becomes $0.06\, H_0^{-1}$.]

Again, for the $q_0 = 0$ case, equation (3) must agree with H_0^{-1} from equation (2), i.e., with the directly determined cosmological value. Hence, substitution of $t_0 = H_0^{-1}$ in equation (3) requires that $0.8\, H_0^{-1} = (17 \pm 2) \times 10^9$ years, or $H_0^{-1} = (21.2 \pm 2.5) \times 10^9$ years via time scales; hence

$$H_0 = 46 \pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad (4)$$

is required for exact agreement of the times. The similarity of equations (2) and (4) indicates the time scale test to be successful. The result may be interpreted in two ways: either (1) the distance scale and the age of the globular clusters are indeed correct, and therefore the $q_0 \approx 0$ Friedmann model does apply, or (2) a Friedmann model is assumed, and then the determinations of H_0 through the distance scale and through the age of the globular clusters lend support to each other.

Given the globular cluster age, Friedmann solutions (i.e., $\Lambda = 0$) do not exist for $H_0 \gtrsim 60$.

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